NBS TECHNICAL NOTE 1107

U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

The Use of Aerial Infrared Thermography to Compare the Thermal Resistances of Roofs

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The Use of Aerial Infrared Thermography to Compare the Thermal Resistances of Roofs

D.M. Burch

Center for Building Technology
National Engineering Laboratory
National Bureau of Standards
Washington, DC 20234

Sponsored by:

Department of Energy
Washington, DC 20585

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The Use of Aerial Infrared Thermography to Compare the Thermal Resistances of Roofs

by

D. M. Burch

ABSTRACT

The paper investigates whether a comparative roof survey using aerial infrared thermography can be used to rank the roofs of residential and commercial buildings according to their thermal resistance. Mathematical models are presented for predicting the apparent radiance temperature of these roof systems. These models are used to investigate the differences in apparent radiance temperature between roofs having various thermal resistances. These predicted differences are then compared with predicted differences in apparent radiance temperature caused by typical variations in roof emittance, local outdoor temperature, and local wind speed throughout the macroclimate. The transmission characteristics of the atmosphere are reviewed, and the required dew-point spread for preventing dew or frost formation on a roof is examined.

Key words: Aerial flyovers; aerial infrared thermography; energy conservation; roof heat-loss survey.

ACKNOWLEDGMENT

The author gratefully acknowledges the contribution of John Bean, who carried out the computer analysis for this study.

Nomenclature

A	=	surface area
C_p	=	specific heat of air
ε	=	surface emittance
E	=	emittance factor
F	=	radiation heat-transfer coefficient
h	=	convection heat-transfer coefficient
I	=	rate of air infiltration
M	=	emitted thermal radiation (exitance)
R	=	thermal resistance
T	=	temperature
V	=	volume
$\dot{V}$	=	air penetration rate per unit ceiling area
W	=	wind speed
θ	=	field of view
ρ	=	density of air
σ	=	Stefan-Boltzmann constant

Subscripts

a	=	apparent radiance property or attic property
c	=	ceiling property
e	=	attic end wall property
f	=	attic floor property
i	=	indoor property
o	=	outdoor environment
r	=	roof property
s	=	soffit (eaves) property
sky	=	calorimetric sky property
sky'	=	spectral sky property

CONVERSION FACTORS TO METRIC (SI) UNITS

Physical Quantity	Symbol	To Convert From	To	Multiply By
Length	ℓ	ft	m	3.05×10^{-1}
Area	A	ft^2	m^2	9.29×10^{-2}
Volume	$\forall$	ft^3	m^3	2.83×10^{-2}
Temperature	T	Fahrenheit	Celsius	$T_C = (T_F - 32)/1.8$
Temp. Diff.	ΔT	Fahrenheit	Kelvin	$K = (\Delta T_F)/1.8$
Density	ρ	lb/ft^3	kg/m^3	$1.602 \times 10^{+1}$
Thermal Transmittance (or Conductance)	U,h	$Btu/h \cdot ft^2 \cdot {}^\circ F$	$W/m^2 \cdot K$	5.68
Thermal Resistance	R	$h \cdot ft^2 \cdot {}^\circ F/Btu$	$m^2 \cdot K/W$	0.176
Heat Flux (Thermal Radiation)	q/A	$Btu/h \cdot ft^2$	W/m^2	3.15
Heat Flow	q	Btu/h	W	2.93×10^{-1}
Volumetric Flow Rate	V	ft^3/min	m^3/s	4.72×10^{-4}
Wind Speed	W	ft/min	m/s	5.08×10^{-3}
Specific Heat	C_p	$Btu/lb \cdot {}^\circ F$	$J/kg \cdot K$	4.19×10^{3}

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THE USE OF AERIAL INFRARED THERMOGRAPHY
TO COMPARE THE THERMAL RESISTANCES OF ROOFS

D. M. Burch

1. INTRODUCTION

Aerial infrared thermography is an imagery process utilizing an infrared line scanner which produces an apparent radiance temperature map of a portion of the terrain underneath an aircraft. Such a process has been shown to be effective in locating regions on low-slope built-up roofs that have defective insulation [1,2]. These regions will show up as "hot spots" in the radiance temperature map. A common problem with built-up roofs is that the exterior membrane becomes ruptured, permitting water to penetrate the roof system and wet the insulation. Regions having wet insulation will conduct more heat and will appear warmer than regions having dry insulation. The merit of such a survey technique is that defective regions can be located, permitting local repairs to be carried out instead of replacing the whole roof system.

Aerial infrared thermography has also been used to compare the thermal resistances of roofs included in an aerial infrared photograph [3-12]. Proponents of such comparative surveys assert that roofs which lose more heat will be warmer and will therefore appear as having higher apparent radiance temperatures. In an aerial infrared photograph, such roofs are said to appear lighter in gray tone than roofs losing less heat. It is normally recommended that aerial infrared surveys <u>not</u> be carried out under an overcast-sky condition, in order to avoid the problem of large variations in sky temperature affecting the apparent radiance temperature. In addition, under a clear-sky condition, radiation exchange with a cold night sky reduces roof temperature below the ambient air temperature and thereby increases roof heat loss. This process will cause the roofs to be displayed in a greater range of gray tones, which increases the contrast in the thermal image.

A controversial issue within the technical community is whether such comparative roof surveys are actually successful in ranking roofs according to their thermal resistance. An aerial infrared photograph may include as much as a square mile of terrain, depending upon the altitude of the flight. Considerable variation in local air temperature and wind speed may exist throughout the macroclimate of an aerial infrared photograph. In addition, roof emittance varies from one roof to the next. Variations in local wind speed, local outdoor temperature, and roof emittance may produce differences in radiance temperatures of roofs which may mask out those differences in radiance temperature due to roof resistance. This paper examines this issue.

This paper also investigates the depression in surface temperature from which the required dew-point spread for preventing the formation of dew or frost on roofs can be determined. It is recommended that aerial infrared surveys be conducted under outdoor conditions which preclude dew or frost from occurring on roofs. The formation of dew or frost on a roof may change its emittance, and the phase change which occurs releases latent heat to the roof which increases its surface temperature. Both of these effects may substantially change the apparent radiance temperature of a roof.

2. CONCEPT OF AERIAL INFRARED THERMOGRAPHY

The basic concept of aerial infrared thermography is that all objects emit thermal radiation according to the Stefan-Boltzmann equation:

$$M = \varepsilon \cdot \sigma \cdot T^4 \tag{1}$$

where M = emitted thermal energy (exitance),
σ = Stefan-Boltzmann constant,
T = absolute temperature, and
ε = surface emittance.

As the heat-loss rate through an exterior surface of a building increases, the exterior surface temperature of that part of the building also increases. The emitted thermal energy as given by eq. (1) will increase if the surface emittance remains constant.

In conducting an aerial infrared survey, an infrared line scanning system mounted in an aircraft scans the terrain, building up a thermal image as the aircraft progresses along a flight line, as shown in figure 1. The scanner is basically an optical telescope, with its narrow field of view continuously redirected by a spinning flat mirror. The mirror causes the system to scan in a plane perpendicular to the direction of flight of the aircraft. Such systems have one or more cryogenically cooled thermal radiation detectors in the focal plane of the telescope which convert the focused thermal energy received by the detector into an electrical signal. This electrical signal can be processed into a visual image on a cathode-ray tube (CRT) which can be photographically recorded or digitized and recorded on a magnetic tape recorder for future processing.[1]

---

[1] Much of this description was taken from ref. [3].

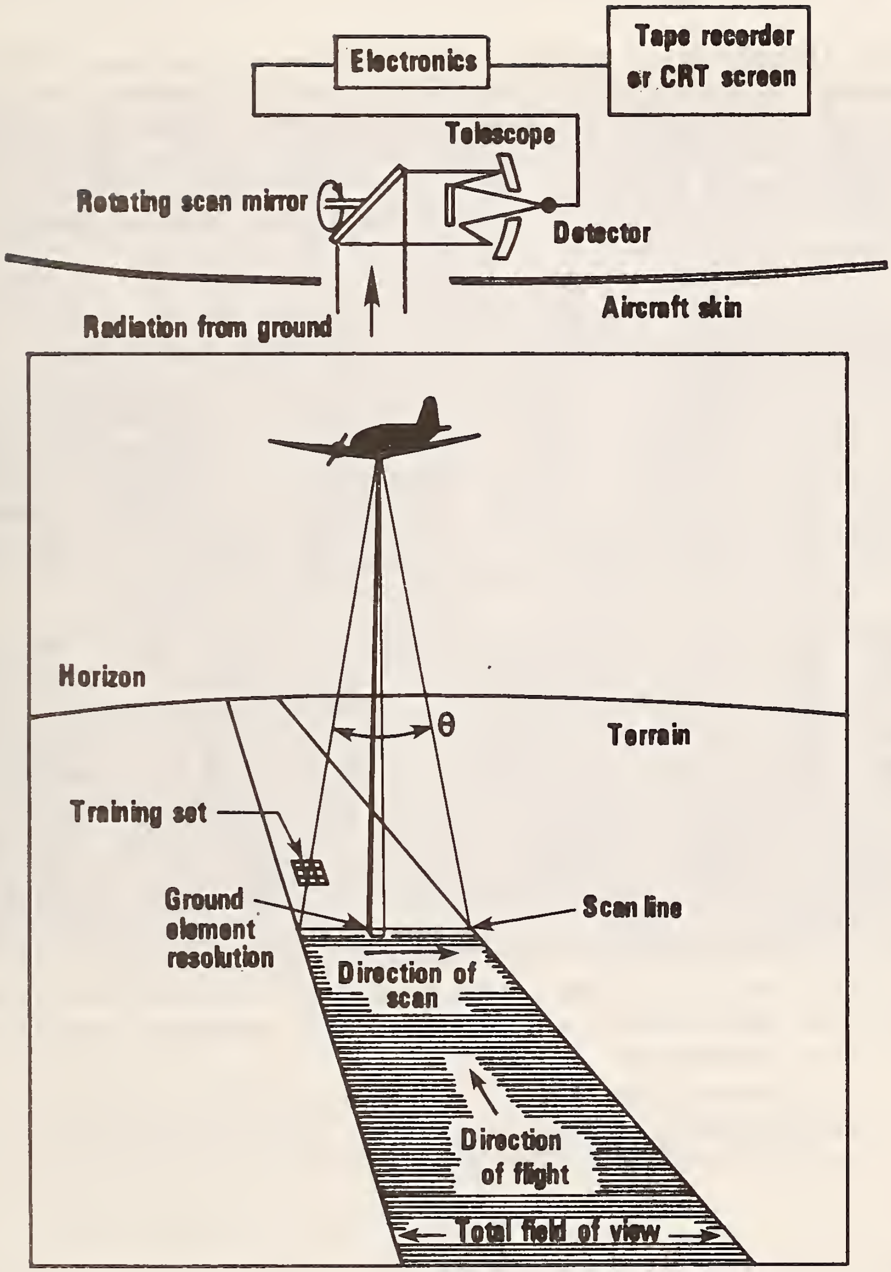

Figure 1. Schematic illustration of the use of a line scanner to perform aerial infrared thermography [3].

An aerial infrared photograph of a large number of residential roofs is shown in figure 2. Variations in gray tone from light to dark correspond directly to variations in apparent radiance temperature. Parts of the thermal picture appearing in lighter gray tones have a higher apparent radiance temperature than other parts of the thermal picture.

Infrared line-scanning systems usually have a sweep angle (θ), as depicted in figure 1, which does not exceed 110 degrees, in order to restrict distortion at the outer edges of the thermal picture [4]. Flights are most often conducted at altitudes between 1000 and 2000 ft. The instantaneous field of view of the infrared line scanner varies with the particular system but will generally range between 1 and 2.5 milliradians on a side.

Aerial infrared thermography is usually performed in the 8 to 14 μm wavelength band because of the high atmospheric transmission over that part of the infrared spectrum (see figure 3). Atmospheric transmittance[2] data presented in figure 4 show that the average atmospheric transmittance at a distance of 1640 ft above ground level is 0.93 and 0.97 at outdoor relative humidities of 95 and 20%, respectively. In addition, the same data show that increases in path length due to increases in the view angle have a very small effect on the atmospheric transmittance over this particular wavelength band.

The thermal radiation sensed from surfaces such as roofs by an infrared line scanner includes both self-emitted thermal radiation and reflected radiation from the sky. The apparent radiance temperature (T_a) is defined as the temperature of a perfectly black surface which would radiate the same amount of thermal radiation as a real surface at a temperature (T_s) and having a surface emittance (ε). An equation relating the apparent radiance temperature of a surface to its actual temperature has been derived by Goldstein [13]. For the convenience of the reader, a derivation for the equation is given below.

For the 8-14 μm wavelength band, the self-emitted energy from a perfectly black surface at the apparent radiance temperature (T_a) is equal to the self-emitted and reflected sky radiation from the actual surface at a temperature (T_s), or

$$T_a^n = \varepsilon \cdot T_s^n + (1-\varepsilon) \cdot (T'_{sky})^n \qquad (2)$$

---

[2] Atmospheric transmittance is defined as the fraction of the flux of infrared radiation which is not absorbed or scattered and is transmitted through a layer of the atmosphere.

Figure 2. An aerial infrared photograph of a large number of residential roofs (this aerial infrared photograph was provided by Texas Instruments of Dallas, Texas).

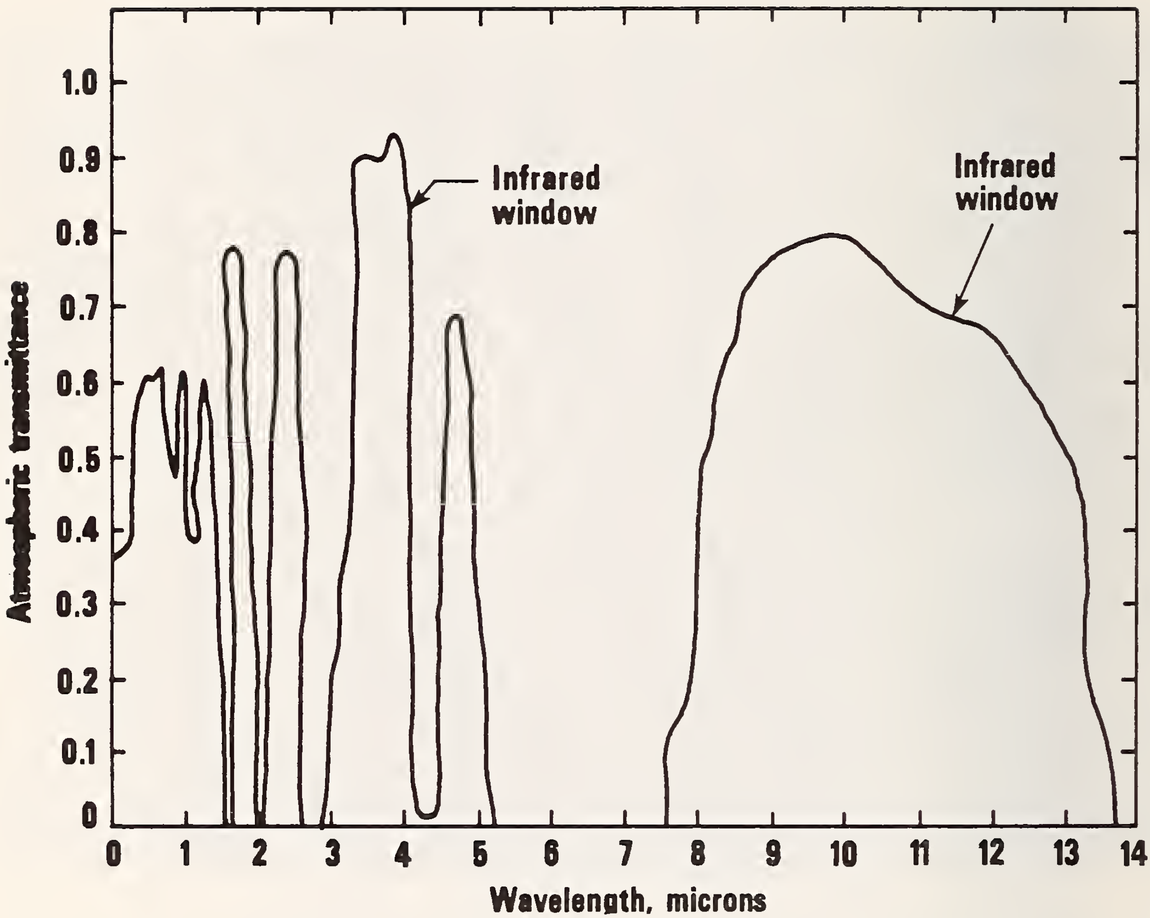

Figure 3. Transmittance of the whole atmosphere as a function of wavelength [5].

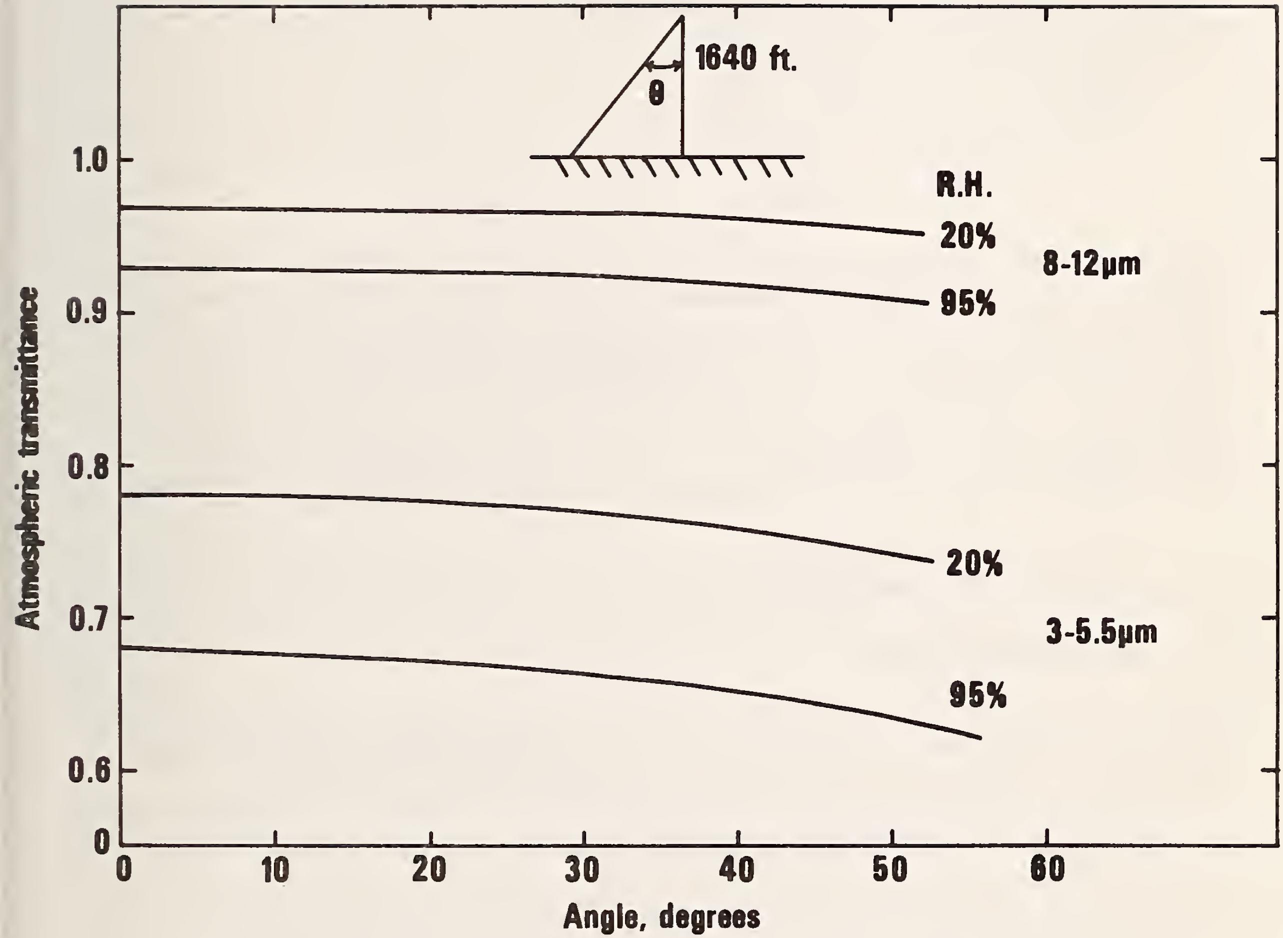

Figure 4. Average atmosphere transmittance as affected by incident angle and outdoor relative humidity [6].

Here the radiant energy from the sky is based on the spectral sky temperature (T'_{sky}) instead of the calorimetric sky temperature (T_{sky}), since radiant energy is being considered only over the 8-14 μm portion of the infrared spectrum.

The spectral sky temperature is lower than the calorimetric sky temperature because the atmosphere is relatively transparent over the 8-14 μm wavelength band. The exponent n is 5 instead of 4 because radiation is only being considered between 8-14 μm instead of the whole infrared spectrum[3].

Solving eq. (2) for T_a gives:

$$T_a = T_s \cdot [\varepsilon + (1-\varepsilon) \cdot \beta^5]^{1/5} \tag{3}$$

Here β is the ratio of the spectral sky temperature (T'_{sky}) to the surface temperature (T_s). The accuracy of equation (3) was investigated by numerically integrating the Planck distribution function for the self-emitted and reflected components of the roof radiance. Equation (3) was found to be accurate within a fraction of a degree Fahrenheit over a representative range of surface temperatures and sky temperatures. It should be pointed out that equation (3) does not account for thermal reflections from nearby buildings.

3. LOW-SLOPE BUILT-UP ROOFS

3.1 MATHEMATICAL MODEL

For a low-slope built-up roof, the steady-state heat conduction through the roof during the night is equal to the heat loss by convection to the ambient outdoor air and the net radiation loss to the sky, or

$$(T_i - T_s)/R = h \cdot (T_s - T_o) + F_o \cdot (T_s - T_{sky}), \tag{4}$$

where

T_i, T_s, T_o, T_{sky} = temperatures of the indoor environment of the building, the exterior surface of the roof, the outdoor air, and the calorimetric sky, respectively,

---

[3] The spectral sky temperature (T'_{sky}) is the equivalent black-body temperature of the sky vault based on sky radiance between 8-14 μm. The calorimetric sky temperature (T_{sky}) is the equivalent black-body temperature of the sky vault based on sky radiance covering the entire infrared spectrum.

h = convection heat-transfer coefficient,

R = thermal resistance of the roof (does not include resistance of the air film at the exterior surface), and

F_o = radiation heat-transfer coefficient.

The radiation heat-transfer coefficient (F_o) is given by the relation:

$$F_o = \varepsilon_s \cdot \sigma \cdot (T_s^2 + T_{sky}^2) \cdot (T_s + T_{sky}) \qquad (5)$$

where ε_s = emittance of the exterior roof surface and

σ = Stefan-Boltzmann constant

Solving eq. (4) for the roof surface temperature (T_s) yields:

$$T_s = \frac{T_i/R + h \cdot T_o + F_o \cdot T_{sky}}{h + F_o + 1/R} \qquad (6)$$

3.2 DESCRIPTION OF ROOF SYSTEM

The built-up roof system used for the analysis was comprised of the following components: 3/8-inch built-up roof membrane; perlite aggregate board; 4-inch concrete deck; and 1/2-inch gypsum plaster. Several thicknesses of perlite aggregate board were considerd in the analysis.

3.3 HEAT-TRANSFER PARAMETERS

Thermal resistance values for the components of the built-up roof system were taken from refs. [15,16] and are summarized in Table 1. In a recent survey of built-up roof systems [17], perlite insulation was found to be the most common type of insulation. This same survey reported the percentage of roofing systems having various insulation thicknesses (see Table 2). For the analysis in this paper, insulation thicknesses of 0, 2, and 4 inches were considered.

The overall thermal resistances for built-up roofs having these insulation thicknesses were calculated using the series resistance method [16]. These values are summarized in Table 3.

3.4 OUTDOOR AND INDOOR PARAMETERS

The indoor temperature below the built-up roof system was taken to be 70°F. A search of the literature was made for emittance values of exterior covering materials and materials which may deposit on built-up roofs. These values are summarized in Table 4. From this table,

Table 1. Thermal Resistance Values* for the Components of the Built-up Roof

Component	Thermal Resistance $h \cdot ft^2 \cdot {}^\circ F/Btu$
3/8-inch Built-up Roof Membrane	0.33
Perlite Aggregate Board (per inch thickness)	2.63
4-inch Concrete Deck	0.32
1/2-inch Gypsum Plaster	0.09
Interior Still Air Film	0.61

* Obtained from refs. [15,16].

Table 2. Survey* of Insulation Thicknesses of Built-up Roof Systems

Percentage of Roof Systems Surveyed	Insulation Thickness, Inch
26	0
21	5/16 -1
41	1 1/16 -2
12	more than 2

* Obtained from ref. [17].

Table 3. Total Thermal Resistance* Values for Built-up Roof Systems

Insulation Thickness, Inches	Total Thermal Resistance $h \cdot ft^2 \cdot {}^\circ F/Btu$
0	1.4
2	6.6
4	11.9

* Includes thermal resistances of the air films.

Table 4. Emittances for Various Exterior Covering Materials and Materials which May Deposit on Built-up Roofs

Material	Emittance	Reference
Aluminum Roofing	0.22	18
Bituminized Roofing Felt	0.91	14
Concrete, rough	0.94	19
Frost, rime	0.99	14
Ice, smooth	0.91	14
Soot	0.95	20
Water	0.97	14
Asphalt	0.93-0.96	5
Dolomite Gravel, 0.5-cm rocks	0.96	27
Snow	0.82	21

Table 5. Calorimetric and Spectral Sky Temperatures Used for the Analysis

Outdoor Temperature °F	Calorimetric Sky Temperature °F	Spectral Sky Temperature °F
0	-54	-121
10	-40	-102
20	-27	- 83
30	-13	- 65
40	0	- 47

it is seen that the emittances of most exterior covering materials vary over a range of 0.91 to 0.96, except for metallic roof surfaces such as aluminum roofing. It is noted that the accumulation of ice, soot, water, or frost can change the roof emittance. Roof emittance will usually have a weak dependence on the view angle, except for view angles exceeding 60° from the normal [5]. For the thermal analysis, the roof emittance was assumed to be 0.90, unless otherwised specified. Calorimetric and spectral sky temperatures for a clear winter sky which were used for the analysis are given in Table 5. The calorimetric sky temperatures are based on measured data of Swinbank [22], and the spectral sky temperatures were obtained from Goldstein [25].

The convection heat-transfer coefficient (h) was calculated using the following relation:

$$h = 0.5 + 0.38 \cdot W. \tag{7}$$

Here W is the wind speed in miles per hour. This equation is based on data for a concrete surface [24] with the radiation portion of the overall heat-transfer coefficient subtracted. Equation (7) applies to a roof that has no obstructions to the flow of air.

3.5 RESULTS AND ANALYSIS

3.5.1 Effect of Thermal Resistance

The mathematical model described in the previous sections was used to predict the difference in apparent radiance temperature between built-up roofs having 0 and 2 inches of perlite insulation under a wide range of outdoor conditions. The results of this analysis are given in figure 5. Under low wind conditions (wind speeds less than 5 mph), the radiance temperature differences between built-up roofs having 0 and 2 inches of insulation are substantially greater than at higher wind speeds. Mean winter wind speeds for the United States are well above 5 mph [23]. It is likely that most aerial infrared surveys would be performed under conditions for which the surface wind speeds would be greater than 5 mph. Under such conditions, the maximum radiance temperature difference between built-up roofs having 0 and 2 inches of insulation would be 12°F. For an outdoor ambient temperature of 20°F and a 10-mph wind speed, the radiance temperature difference between these roofs would be 5°F, which perhaps could be considered a representative value.

Predicted differences in apparent radiance temperature between the exterior surfaces of built-up roofs having 2 and 4 inches of insulation are given in figure 6. These temperature differences are seen to be considerably less than those between roofs having 0 and 2 inches of insulation. For wind speeds in excess of 5 mph, the difference in apparent radiance temperature is seen to be less than 2°F.

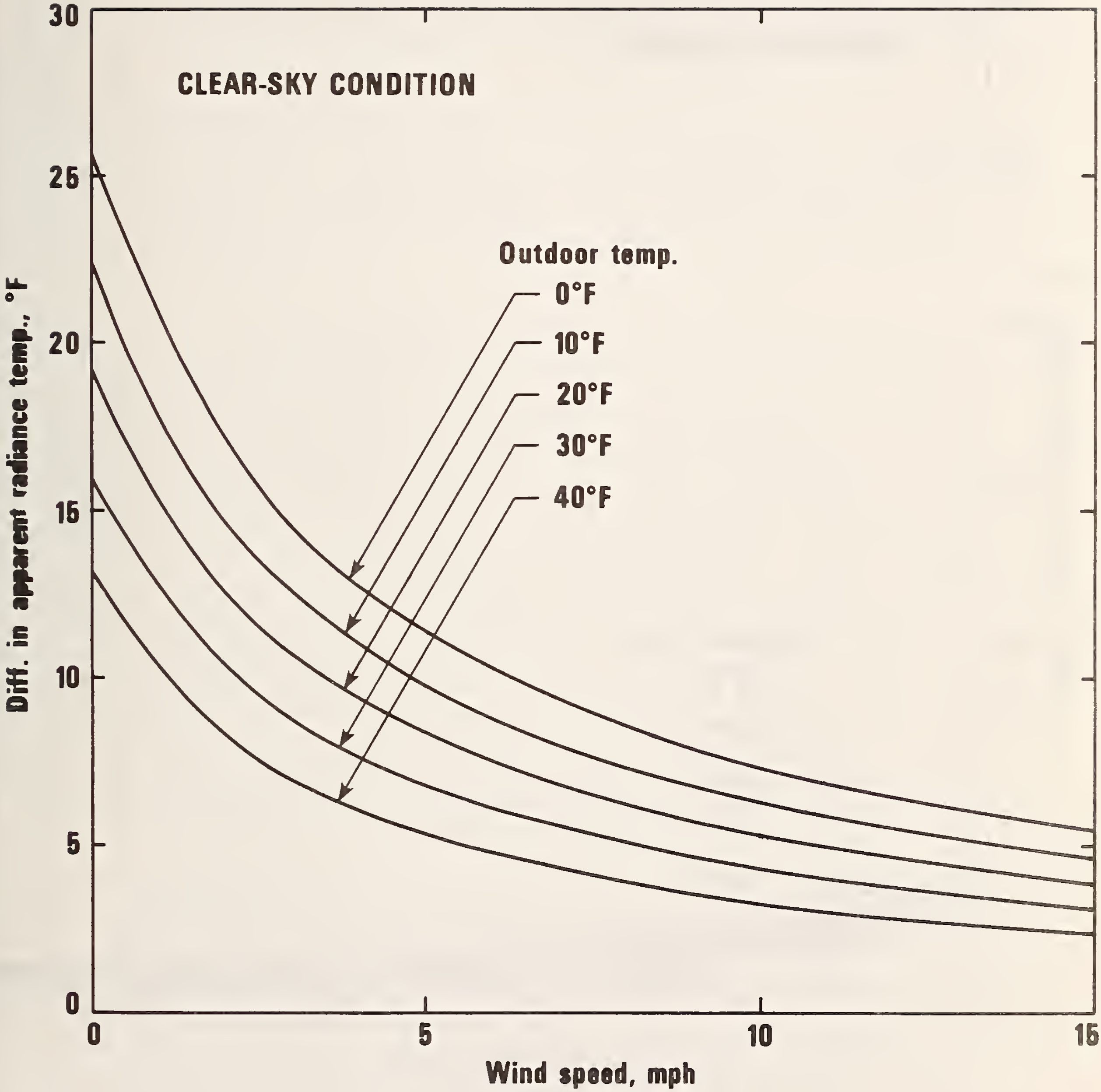

Figure 5. Predicted differences in apparent radiance temperature between the exterior surfaces of built-up roofing systems having 0 and 2 inches of insulation as a function of wind speed for various outdoor temperatures.

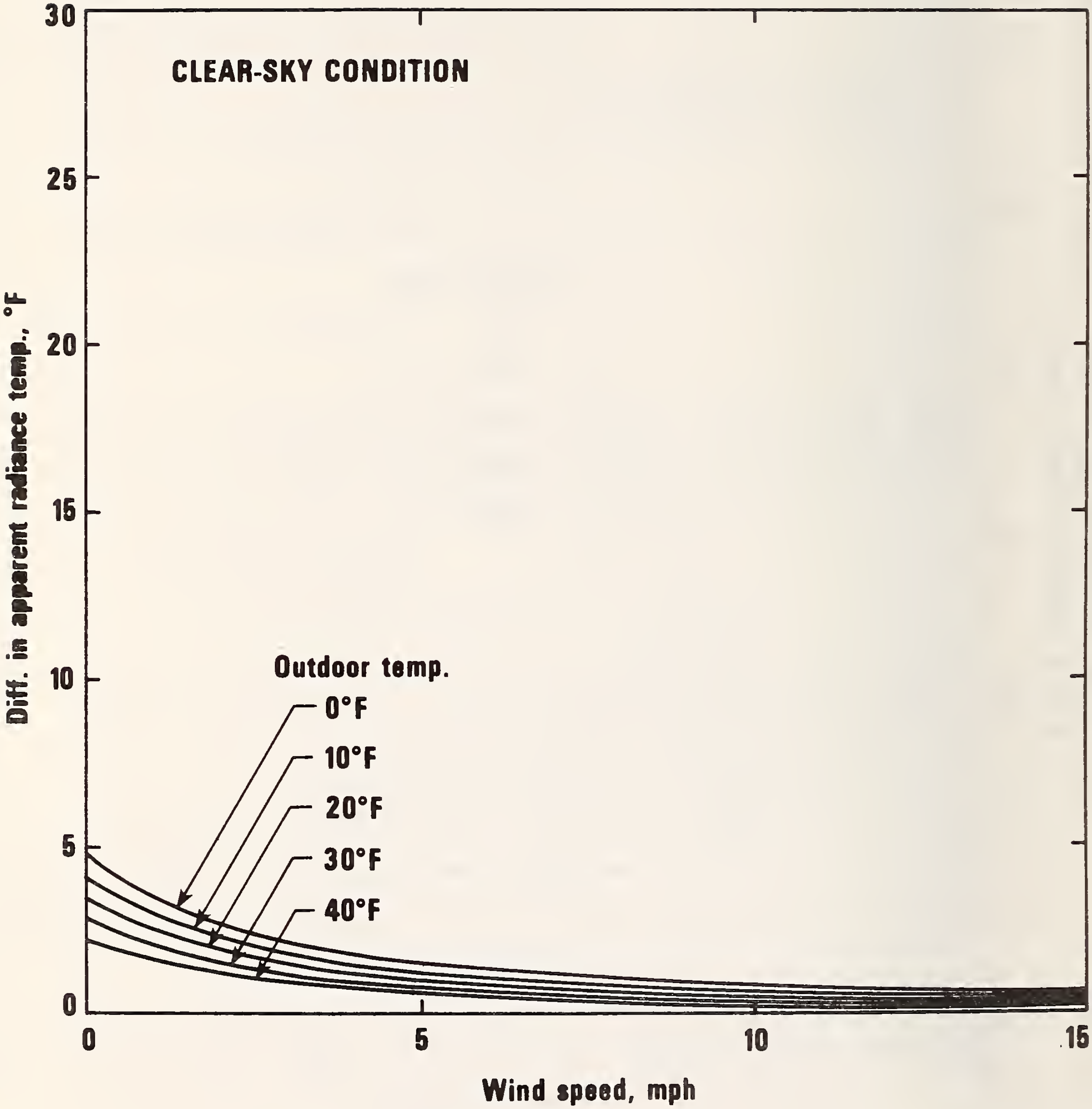

Figure 6. Predicted differences in apparent radiance temperature between the exterior surfaces of built-up roofing systems having 2 and 4 inches of insulation as a function of wind speed for various outdoor temperatures.

3.5.2 Effect of Other Parameters

In this section, the mathematical model is used to compare differences in radiance temperature between roofs having different thermal resistances to differences in radiance temperatures resulting from variations in roof emittance, local outdoor temperature, and local wind speed. For this analysis, the outdoor temperature of the macroclimate is taken to be 20°F.

The difference in radiance temperature between two roofs, one having no insulation and the other having 2 inches of insulation, is given in curve a of figure 7. The emittance of these two roofs was taken to be 0.9. Similarly, the radiance temperature difference between two roofs, one having 2 and the other having 4 inches of insulation, is given in curve b of figure 7.

Differences in radiance temperature due to variations in roof emittance, local outdoor temperature, and local wind speed for a roof with 2 inches of insulation are also plotted in figure 7. Curve c gives the difference in radiance temperature between two roofs, one having an emittance of 0.9 and the other having an emittance of 1.0. Such an emittance range is consistent with the range in emittances of common roofing materials given in Table 4. Curve d gives the difference in radiance temperature between two roofs, one exposed to a local outdoor temperature of 20°F and the other exposed to a local outdoor temperature of 25°F. It was believed that a 5°F variation in the local outdoor temperature throughout a macroclimate would be representative of actual conditions. And finally, curve e gives the difference in radiance temperature between two roofs, one exposed to a particular wind speed and the other exposed to a fifty percent reduced wind speed. Variations in terrain elevation (such as hills and high-rise buildings) will shelter certain roofs from the wind. It was assumed for this analysis that such sheltered roofs would be exposed to winds having one half the wind speed of unsheltered roofs. Similar results were obtained for roofs having different insulation thicknesses.

From this analysis, it can be seen that variations in roof emittance, local wind speed, and local outdoor temperature produce differences in radiance temperature which mask out those differences in radiance temperature between roofs having 2 and 4 inches of insulation. Therefore, it will often be difficult to distinguish a roof with 2 inches of insulation from one having 4 inches of insulation. On the other hand, the differences in radiance temperature between roofs having 0 and 2 inches of insulation are larger than those differences in radiance temperature due to variations in other parameters when the wind speed is less than 7.5 mph. Therefore, there is a good chance of distinguishing a roof having 0 inches of insulation from one having 2 inches of insulation, particularly if the wind speed is less than 7.5 mph.

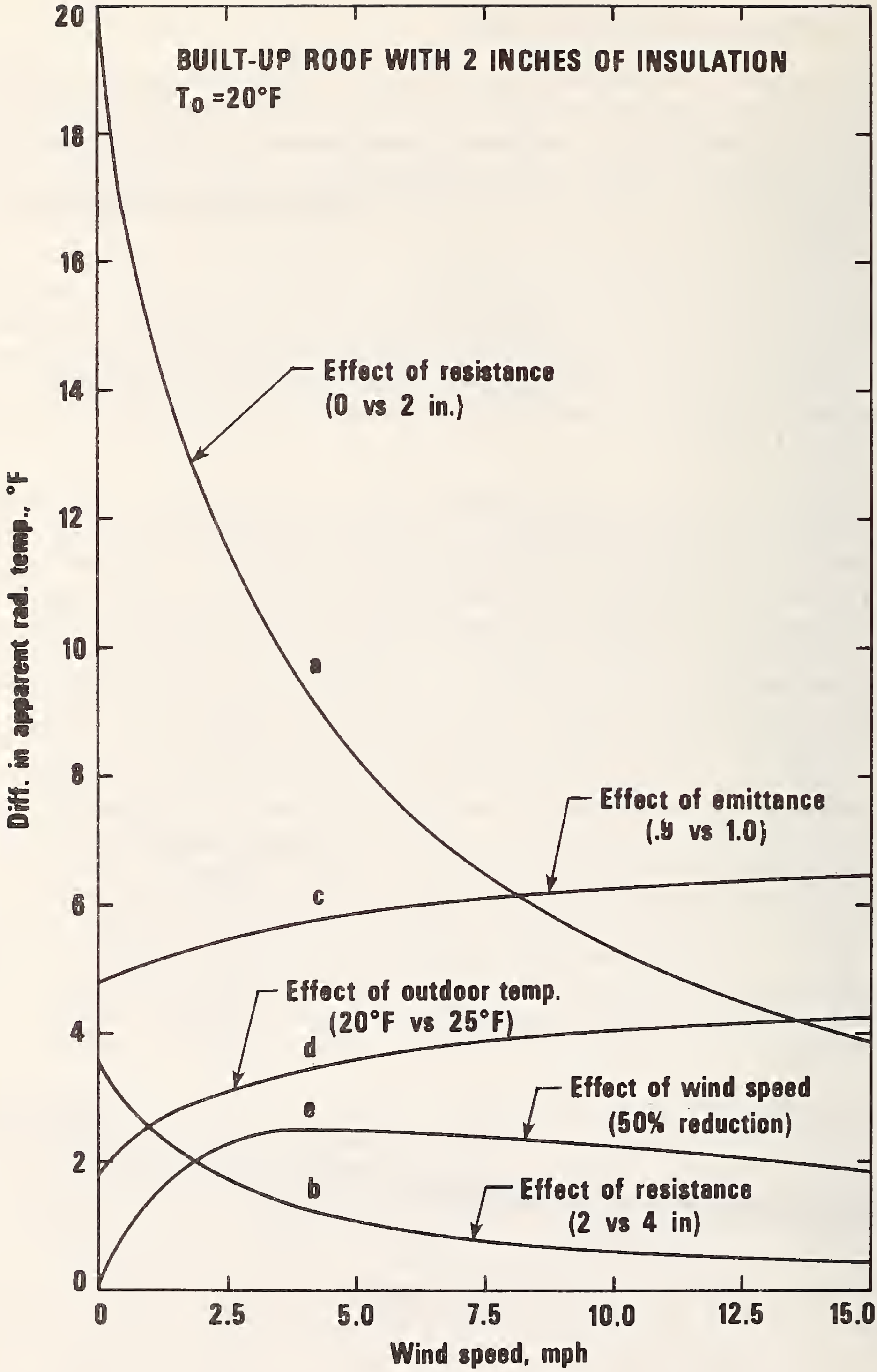

Figure 7. A comparison of the effect of emittance, thermal resistance, local wind speed and local outdoor temperature on the apparent radiance temperature of a built-up roof having 2 inches of insulation.

3.5.3 Dew-Point Spread

The mathematical model was also used to investigate the depression in surface temperature for a built-up roof due to radiation exchange with a clear night sky (see figure 8). For the analysis, the built-up roof having 4 inches of insulation was used, since the depression in surface temperature would be greater for this roof than for roofs having lesser insulation. Dew or frost would form on this roof before it would form on roofs having less thermal insulation. A criterion for precluding the formation of dew or frost would be that the dew-point spread (difference between the dry-bulb and dew-point temperatures) of the outdoor air should be larger than the depression in surface temperature.

To illustrate the use of figure 8, consider the following example: An aerial infrared survey is carried out at an outdoor temperature of 20°F and a relative humidity of 75%. The dew-point temperature corresponding to this psychrometric condition is 14°F, giving a dew-point spread of 6°F. From figure 8, the depression in surface temperature for wind speeds less than 7 mph is greater than 6°F. Therefore, if this aerial infrared survey is to be performed without dew or frost formation on a built-up roof, then the local outdoor wind speed should be greater than 7 mph.

Under still-air conditions, the radiation exchange between a roof and a cold night sky can reduce the surface temperature as much as 19°F below the ambient air (see figure 8). This figure agrees with measured data of Cullen [28] which show as much as a 20°F depression in the surface temperature of a roof due to radiation exchange with a cold night sky. As the wind speed across a roof increases, the roof temperature approaches the outdoor air temperature and the likelihood of dew or frost formation is reduced substantially.

4. PITCHED VENTILATED ROOFS

4.1 MATHEMATICAL MODEL

A mathematical model for predicting the exterior surface temperature of a pitched ventilated roof is presented herein. Using the attic space as a control volume for a steady-state heat balance, the rates of heat gain into the attic space by way of convection from the attic floor and air penetration through the attic floor are equal to the rates of heat loss by convection to the roof, heat conduction through the soffit region and attic end walls, and the rate of heat loss due to the exchange of attic air with outdoor air, or:

$$A_c \cdot h_f \cdot (T_f - T_a) + \dot{V} \cdot A_c \cdot C_p \cdot \rho \cdot (T_i - T_a) = A_r \cdot h_r \cdot (T_a - T_r) +$$

$$A_s \cdot (T_a - T_o)/R_s + A_e \cdot (T_a - T_o)/R_e + I_a \cdot \rho \cdot C_p \cdot V_a \cdot (T_a - T_o), \qquad (8)$$

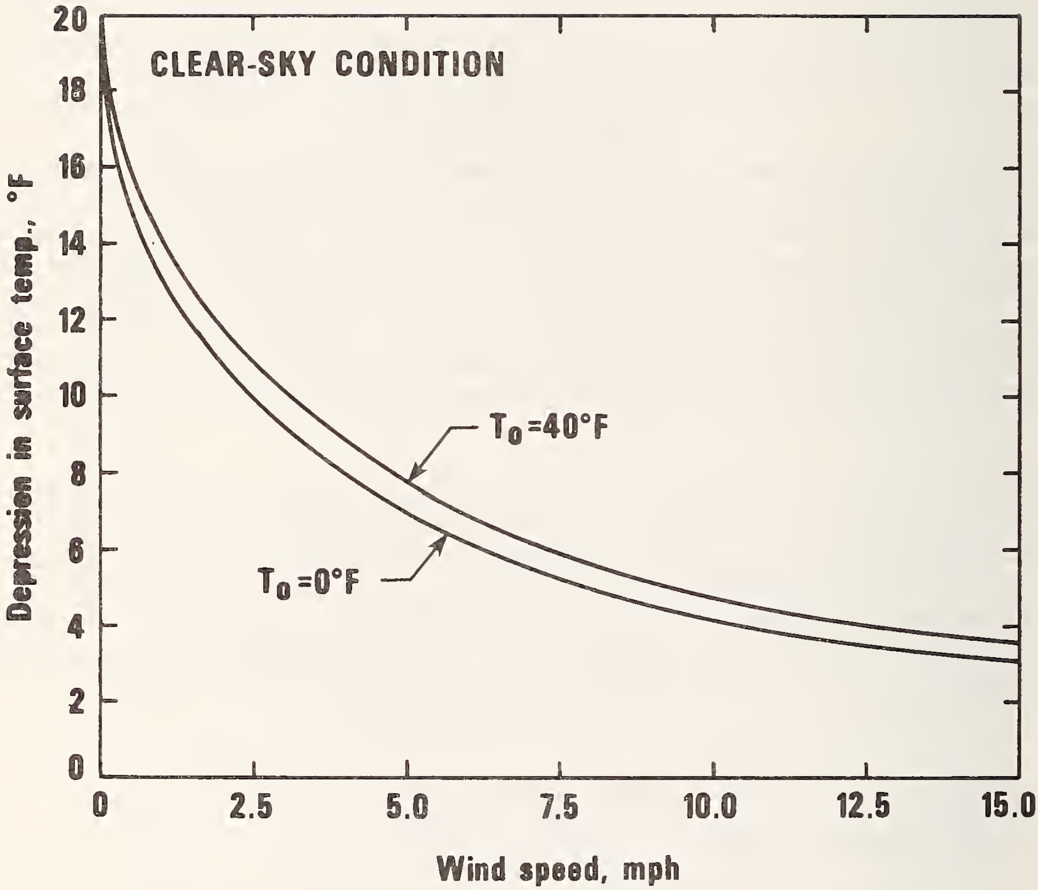

Figure 8. Depression in surface temperature on a built-up roof having 4 inches of insulation as a function of wind speed.

where T_i, T_a, T_f, T_r = temperatures of the indoor air, attic space air, surface of attic floor, and underside of the roof, respectively,

A_c, A_r, A_s, and A_e = surface areas of the ceiling, roof, soffit (eaves) region, and attic end walls, respectively,

I_a = attic ventilation rate,

ρ = density of air,

C_p = specific heat of air,

V_a = volume of the attic space,

$\dot{V}$ = rate of air penetration per unit ceiling area, and

h_f, h_r = convection heat-transer coefficients for the attic floor and underside of the roof.

Performing a heat balance on a unit area of attic floor, the rate of heat conduction through the attic floor is equal to the convective heat loss and the net radiation exchange between the attic floor and the underside of the roof, or:

$$(T_i - T_f)/R_c = h_f \cdot (T_f - T_a) + F_a \cdot (T_f - T_r), \tag{9}$$

where R_c = thermal resistance of the attic floor (ceilng) and

F_a = radiation heat-transfer coefficient between the attic floor and the underside of the roof.

The other symbols are as previously defined. The thermal resistance of the attic floor (ceiling) (R_c) does not include the air film resistance at the attic floor. The radiation heat-transfer coefficient (F_a) is defined by the relation:

$$F_a = E \cdot \sigma \cdot (T_f^2 + T_r^2) \cdot (T_f + T_r) , \tag{10}$$

where E = emittance factor (see eq. 18) and

σ = Stefan-Boltzmann constant.

Performing a similar heat balance on a unit area of the underside of the roof, the rate of heat conduction through the roof is equal to the convective heat gain from the attic air and the net radiation exchange from the attic floor to the underside of the roof, or

$$(T_r - T_s)/R_r = h_r \cdot (T_a - T_r) + F_a \cdot (T_f - T_r), \tag{11}$$

where T_s = temperature of the exterior surface of the roof and

R_r = thermal resistance of the roof.

The thermal resistance (R_r) does not include the air-film resistances at the exterior and interior surfaces of the roof. The radiation heat-transfer coefficient is defined by equation (10).

At the exterior surface of the roof, the rate of heat conduction through the roof is equal to the rate of convection heat loss to the ambient air and the radiation heat-loss rate to the sky, or:

$$(T_r - T_s)/R_r = h_o \cdot (T_s - T_o) + F_o \cdot (T_s - T_{sky}), \tag{12}$$

where h_o = convection heat-transfer coefficient at the exterior surface,

F_o = radiation heat-transfer coefficient between the roof and sky,

T_o, T_{sky} = temperatures of the outdoor air and the sky, respectively.

Equations (8), (9), (11), and (12) can be rearranged respectively as follows:

$$\left(h_f + \dot{V} \cdot C_p \cdot \rho + \frac{A_r}{A_c} \cdot h_r + \frac{A_s}{A_c} \cdot \frac{1}{R_s} + \frac{A_e}{A_c} \cdot R_e + I_a \cdot \rho \cdot C_p \cdot \frac{V_a}{A_c}\right) \cdot T_a$$

$$-h_f \cdot T_f - \frac{A_r}{A_c} \cdot h_r \cdot T_r = \dot{V} \cdot C_p \cdot \rho \cdot T_i + \left(\frac{A_s}{A_c} \frac{1}{R_s} + I_a \cdot \rho \cdot C_p \cdot \frac{V_a}{A_c} + \frac{A_e}{A_c} \cdot \frac{1}{R_e}\right) \cdot T_o \tag{13}$$

$$-F_a \cdot T_r + (1/R_c + h_f + F_a) \cdot T_f - h_f \cdot T_a = T_i/R_c \tag{14}$$

$$(1/R_r + h_r + F_a) \cdot T_r - F_a \cdot T_f - h_r \cdot T_a - T_s/R_r = 0 \tag{15}$$

$$-\frac{1}{R_r} \cdot T_r + T_s \cdot \left(\frac{1}{R_r} + h_o + F_o\right) = h_o \cdot T_o + F_o \cdot T_{sky} \cdot \tag{16}$$

These four linear algebraic equations for T_f, T_a, T_r, and T_s can be solved simultaneously. An iterative procedure is required, however, in order to converge to values for F_a and F_o.

4.2 DESCRIPTION OF ROOF SYSTEM

A schematic drawing of the attic model is given in figure 9. Using this attic model, the surface areas of the ceiling (A_c), the soffit (eaves) region (A_s), the attic end walls (A_e), and the roof (A_r) were determined and the following dimensionless ratios of physical parameters were defined:

$A_r/A_c = 1.16$; $A_e/A_c = 0.187$; and
$A_s/A_c = 0.0667$; $V_a/A_c = 3.73$.

The mathematical model developed in the previous section was expressed in terms of dimensionless ratios with the idea that such ratios would vary much less than the physical parameters themselves from one attic to the next. The construction details of various components comprising the attic model were selected as follows: the roof consisted of shingles and roofing paper laid on top of 1/2-inch plywood sheathing which was nailed to nominal 2 x 6-inch rafters placed 16 inches on center; the soffit region consisted of 1/2-inch plywood sheathing; the attic end walls were comprised of wood-bevel siding attached to 1/2-inch insulating sheathing, which was nailed to nominal 2 x 4-inch studs placed 16 inches on center; and the ceiling consisted of 1/2-inch gypsum board attached to nominal 2 x 6-inch joists placed 16 inches on center. Various amounts of ceiling insulation were considered (see Table 6).

Table 6. Thermal Resistances of the Components of the Attic

Component	Thermal Resistance $h \cdot ft^2 \cdot {}^\circ F/Btu$
Roof	1.50
Soffit (eaves) region	1.83
Attic End Wall	3.57
Ceiling	
° No Insulation	1.19
° R-11 Insulation	11.3
° R-30 Insulation	28.7

4.3 HEAT-TRANSFER PARAMETERS

The thermal resistances of the various components of the attic space were calculated using the series resistance method as outlined in ref. [16]. For these calculations, wood structural members were

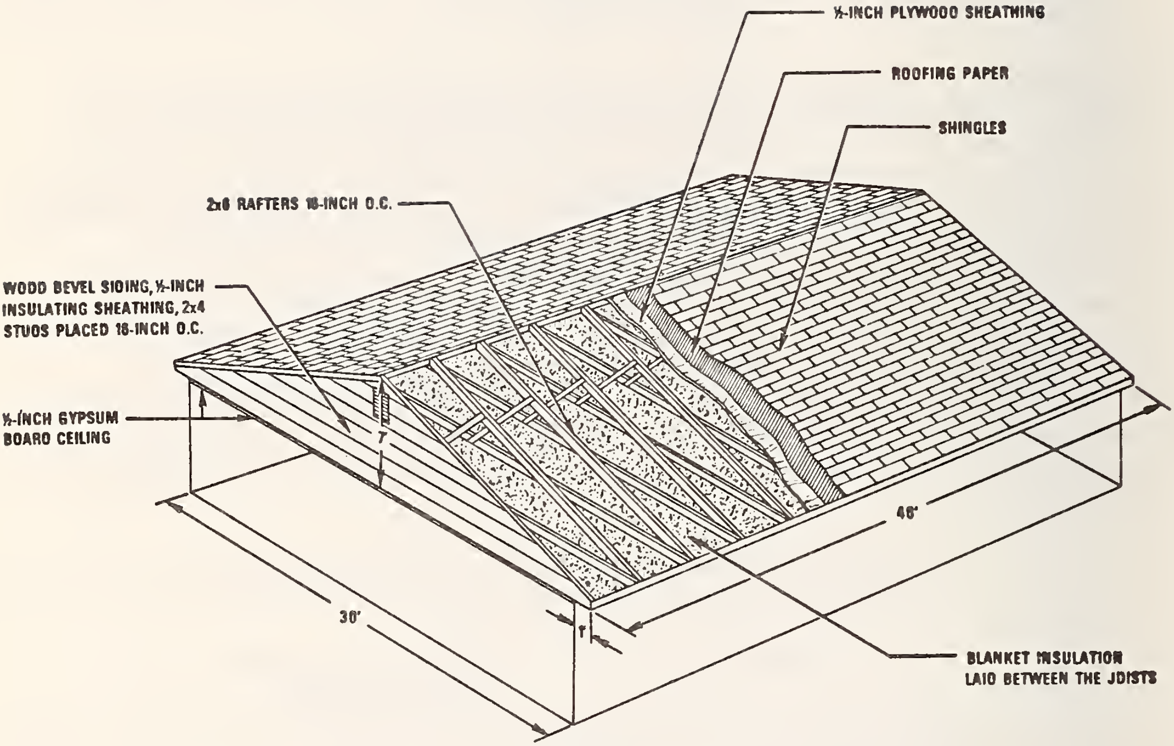

Figure 9. Schematic drawing of roof system.

treated as parallel heat-flow paths. Thermal resistance values for the various components were taken from ref. [16]. Thermal resistance values for the various components of the attic are summarized in Table 6.

The thermal resistance values for the soffit (eaves) region and attic end walls include the thermal resistances of the air films at the exterior and interior surfaces. The value for the roof does not include the air film, while the attic floor (ceiling) values include the air film at the interior surface (living-space side). The convection heat-transfer coefficient (h) at the underside of the roof and floor were assumed to be governed by the relation:

$$h = 0.2 \cdot (\Delta T)^{0.33}. \tag{17}$$

Here ΔT is the surface-to-air temperature difference. This relation is applicable to natural convection heat-transfer with heat flow in an upward direction. The emittance factor (E) was calculated using the relation:

$$E = \frac{1}{\frac{1}{\varepsilon_f} + \frac{1}{\varepsilon_r} - 1} \tag{18}$$

where ε_f and ε_r are the emittances of the attic floor and the underside of the roof. Taking the emittance values to be 0.9, the emittance factor (E) is found to be 0.82.

The attic was assumed to have a natural ventilation rate of 2 volume changes per hour, unless specified otherwise. The rate of convective air penetration through the ceiling was taken to be 0.025 ft^3/min per square foot of ceiling. This figure is based on a house overall air infiltration rate of 0.75 volume changes per hour. It was assumed that 25% of the house exfiltration occurred through cracks in the ceiling construction.

The most common exterior surface covering for the roofs of residences is asphalt shingles. Emittance values for asphalt shingles could not be found in the literature. It was estimated that the surface emittance of asphalt shingles would probably be between 0.85 and 0.95 [26]. Variations would be due to differences in such factors as surface roughness, density and type of top covering material, dust and soot deposits, moisture absorption, etc. For this analysis, the emittance of the shingles of the roof was taken to be 0.90, unless specified otherwise.

4.4 OUTDOOR AND INDOOR PARAMETERS

The outdoor and indoor parameters used for the analysis were the same as those used for the built-up roof analysis given in section 3.4.

4.5 RESULTS AND ANALYSIS

As in the case of the previous section, the mathematical model was used to predict differences in radiance temperature between ventilated pitched roofs having R-0 and R-11 ceiling insulation (see figure 10) and ventilated pitched roofs having R-11 and R-30 ceiling insulation (see figure 11). These differences in radiance temperature are seen to be approximately a factor of 3 smaller than corresponding differences in radiance temperature between built-up roofs having various insulation thickness (see figures 5 and 6). This is due to the decoupling of the roof from the attic floor by the ventilated attic space.

As in the case of the previous section on built-up roofs, the mathematical model was used to compare the differences in radiance temperature caused by variations in roof emittance, local wind speed, and local outdoor temperature to those differences due to variations in ceiling thermal resistance. For this analysis, the range in emittance was taken to be 0.85 to 0.95, sheltered roofs were assumed to be exposed to fifty percent lower wind speeds, and some regions within the macroclimate were assumed to have a local outdoor ambient temperature of 5°F higher than other regions. In addition, the effect of changing the attic ventilation rate from 2 to 4 volume changes per hour was investigated. The outdoor temperature was taken to be 20°F.

The results of this analysis are presented graphically in figure 12. The effect of variations in roof emittance (curve c), local wind speed (curve e), and local outdoor temperature (curve d) on the radiance temperature are seen to be approximately the same magnitude as for the case of the built-up roof (see figure 7). However, the differences in radiance temperature between ventilated pitched roofs having R-0 and R-11 ceiling insulation (curve a) and those having R-11 and R-30 ceiling insulation (curve b) are seen to be usually smaller than those differences in radiance temperature caused by variations in roof emittance (curve c). This means that the effect of an emittance range from 0.85 to 0.95 makes it difficult, if not impossible, to distinguish insulation levels in pitched ventilated roofs. For wind speeds in excess of 4 mph, variations in local wind speed (curve e) and local outdoor temperature (curve d) throughout the macroclimate produce differences in radiance temperature which mask out those differences in radiance temperature due to ceiling thermal resistance. It is interesting to note that varying the attic ventilation rate from 2 to 4 volume changes per hour (curve f) has an insignificant effect on the radiance temperature of the roof. This is because the radiation exchange between the attic floor and the underside of the roof is large in comparison with that from convective heat-transfer processes.

The mathematical model was also used to predict the depression in surface temperature for a ventilated pitched roof having R-30 ceiling insulation (see figure 13). Comparing figure 8 to figure 13, it is seen that the depression in surface temperature is slightly greater for the ventilated pitched roof than for the built-up roof.

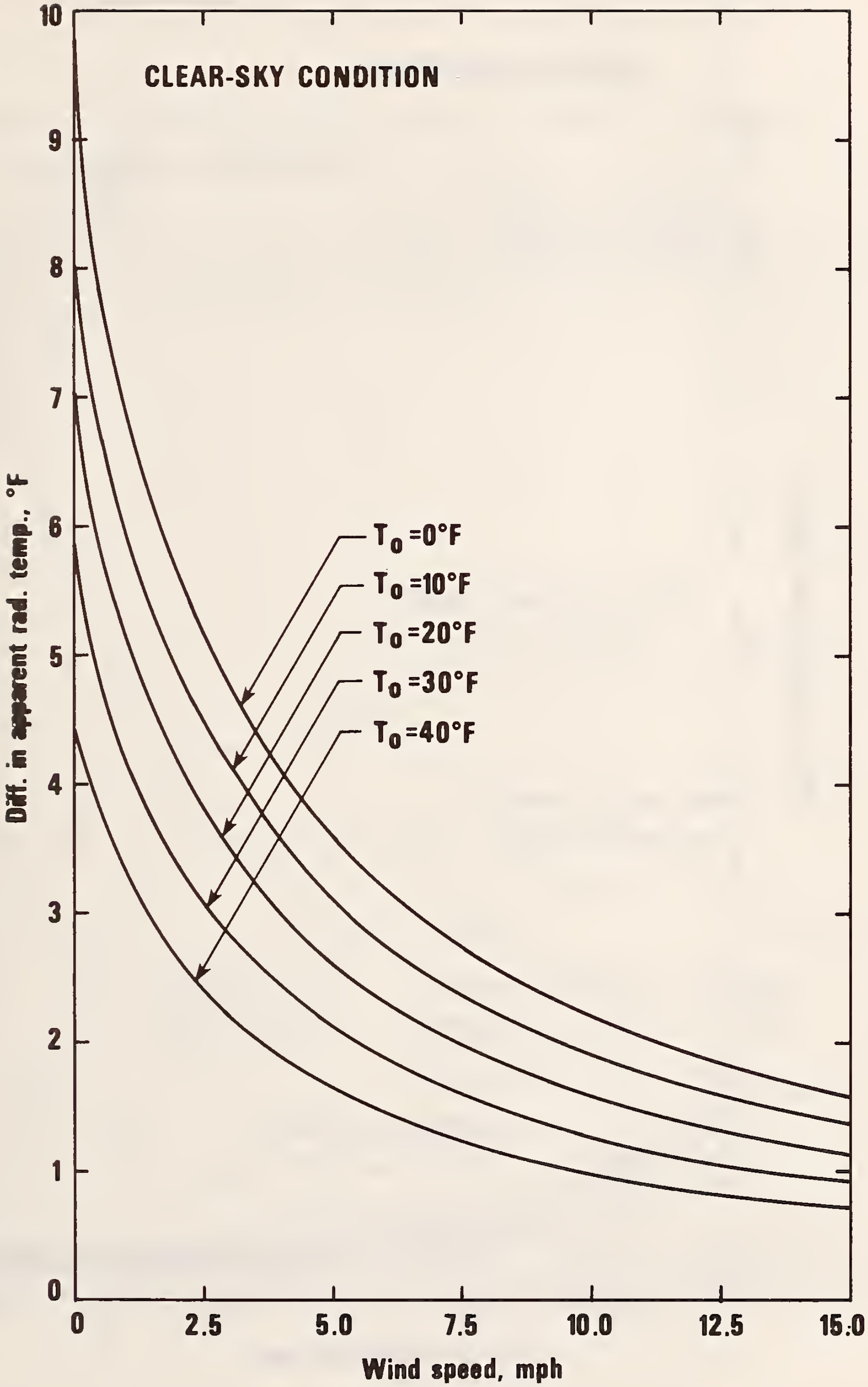

Figure 10. Predicted differences in apparent radiance temperatures between the exterior surfaces of ventilated pitched roofs having R-0 and R-11 ceiling insulation as a function of wind speed for various outdoor temperatures.

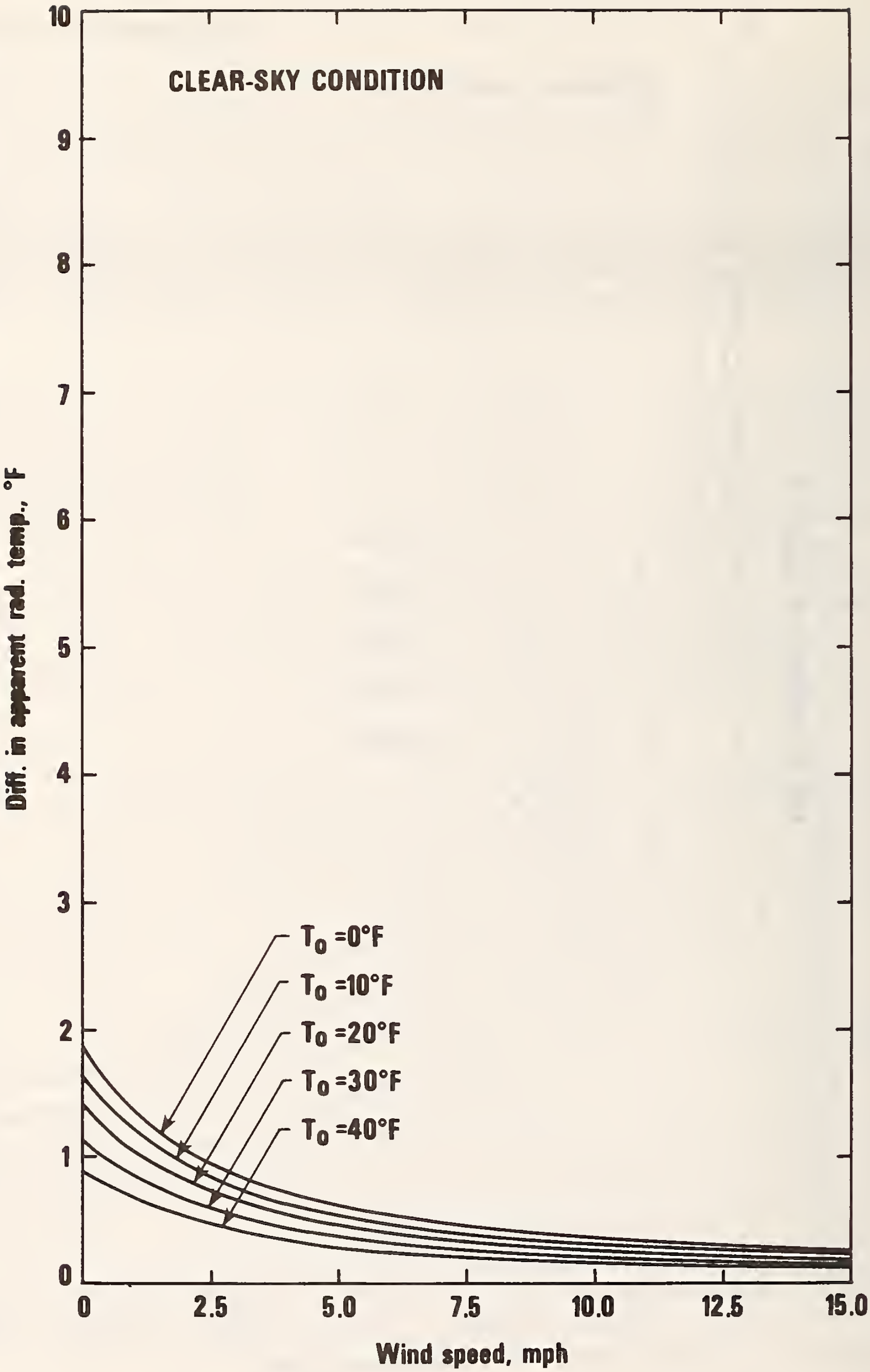

Figure 11. Predicted differences in apparent radiance temperatures between the exterior surfaces of ventilated pitched roofs having R-11 and R-30 ceiling insulation as a function of wind speed for various outdoor temperatures.

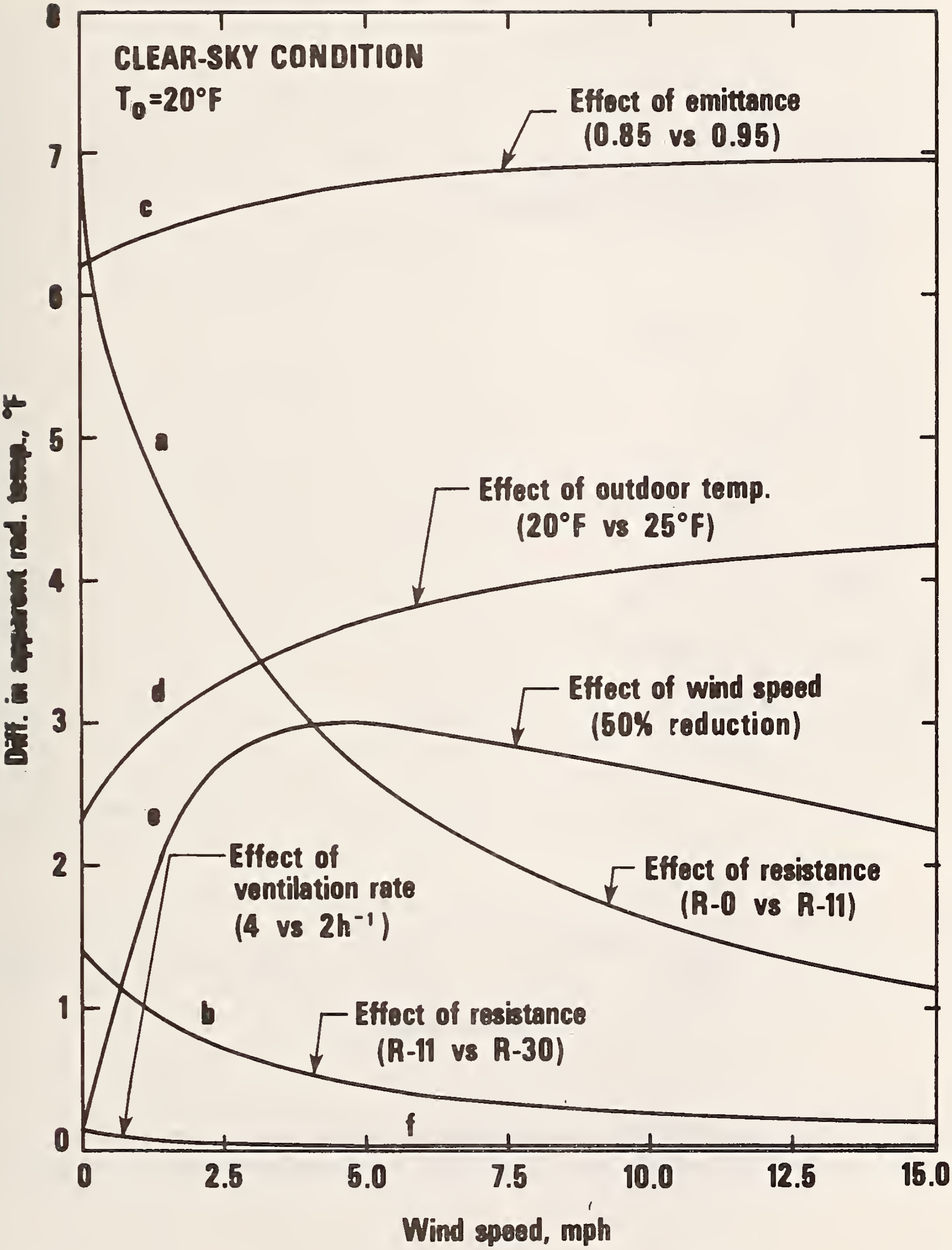

Figure 12. A comparison of the effect of emittance, thermal resistance, local wind speed, and local outdoor temperature on the apparent radiance temperature of a pitched ventilated roof.

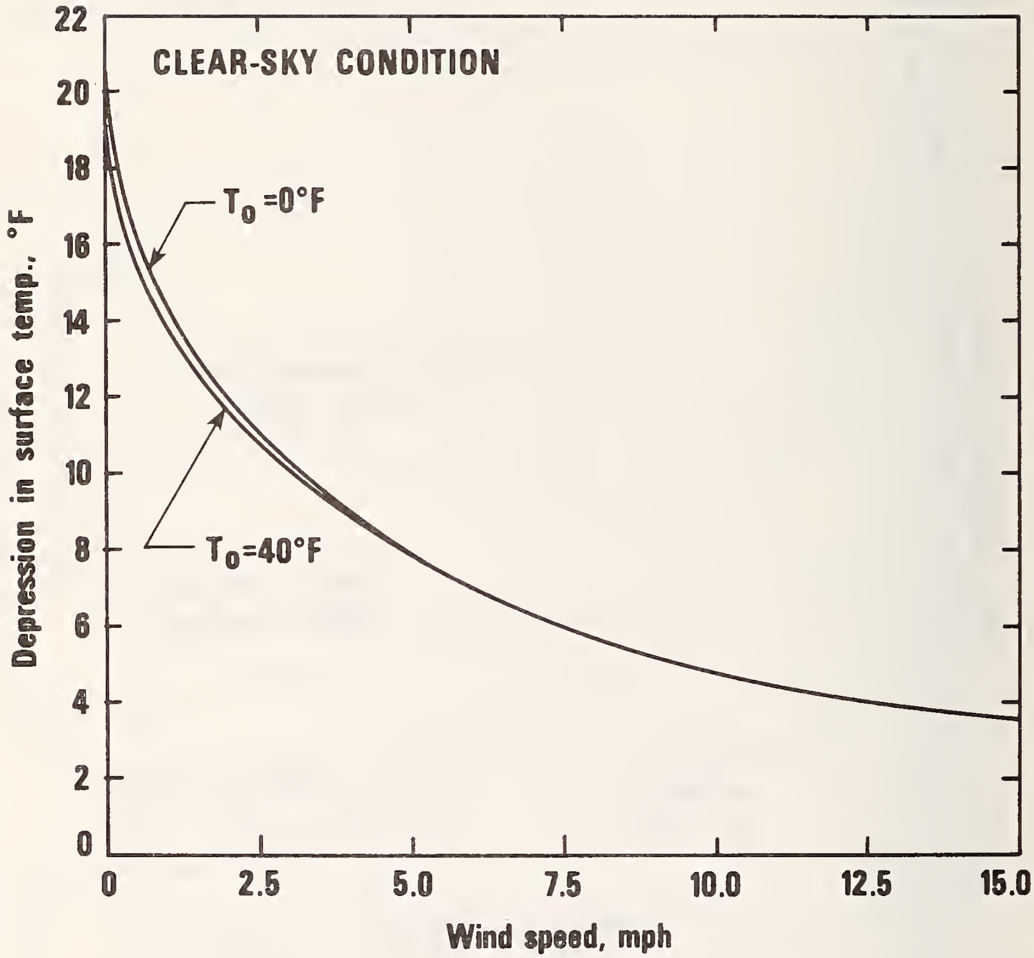

Figure 13. The depression in surface temperature for a pitched ventilated roof having R-30 ceiling insulation as a function of wind speed.

5. SUMMARY AND CONCLUSIONS

When aerial infrared surveys of pitched ventilated roofs are carried out under optimum and preferred clear-sky conditions, variations in roof emittance and variations in local wind speed and local outdoor temperature throughout the macroclimate were shown to cause differences in apparent radiance temperature which mask out those differences in radiance temperature due to variations in ceiling thermal resistance. In other words, gray tone differences between pitched ventilated roofs observed in an aerial infrared photograph were found more likely to be due to variations in roof emittance and variation in local wind speed and local outdoor temperature thoughout the macroclimate than due to variations in ceiling thermal resistance.

In the case of low-slope built-up roofs, variations in roof resistance cause differences in apparent radiance temperature among the roofs displayed in an aerial infrared photograph which are approximately a factor of three greater than those for pitched ventilated roofs. Variations in roof emittance and variations in local wind speed and local outdoor temperature throughout the macroclimate produced differences in radiance temperature which were larger than those between built-up roofs having 2 and 4 inches of insulation, but smaller than those between built-up roofs having 0 and 2 inches of insulation. Therefore, there is a good chance that built-up roofs which have little or no roof insulation will be displayed in a lighter gray tone than more insulated built-up roofs included in an aerial infrared photograph. However, if all the built-up roofs displayed in an aerial infrared photograph are well insulated, then variations in other parameters such as roof emittance, local wind speed, and local outdoor temperature may also cause particular roofs to appear warmer than other roofs, which may be incorrectly interpreted as the absence of roof insulation.

The optimum condition for carrying out an aerial infrared survey is a low-wind condition. As the wind speed decreases, differences in radiance temperature due to variations in roof resistance become larger. Under such a condition, differences in radiance temperature caused by variation in roof emittance, local wind speed, and local outdoor temperature are less likely to mask out those differences due to roof resistance. However, the depression in surface temperature and corresponding required dew-point spread under such a condition becomes large. For instance, the required dew-point spread was shown to vary between 20 and 8°F for wind speeds ranging from 0 and 5 mph.

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The paper investigates whether a comparative roof survey using aerial infrared thermography can be used to rank the roofs of residential and commercial buildings according to their thermal resistance. Mathematical models are presented for predicting the apparent radiance temperatures of these roof systems. These models are used to investigate the differences in apparent radiance temperature between roofs having various thermal resistances. These predicted differences are then compared with predicted differences in apparent radiance temperature caused by typical variations in roof emittance, local outdoor temperature, and local wind speed throughout the macroclimate. The transmission characteristics of the atmosphere are reviewed, and the required dew-point spread for preventing dew or frost formation on a roof is examined.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Aerial flyovers; aerial infrared thermography; energy conservation; roof heat-loss survey.

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